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INVESTIGATION OF SPUTTERING EFFECTS  
ON THE MOON'S SURFACE

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# TABLE OF CONTENTS

<u>Section</u>	<u>Title</u>	<u>Page</u>
	ABSTRACT	iii
I.	INTRODUCTION	1
II.	EROSION RATES DUE TO PHYSICAL SPUTTERING BY THE SOLAR WIND	9
III.	OPTICAL PROPERTIES OF THE MOON AND OF LABORATORY SAMPLES	20
IV.	THE EXISTENCE OF DARKENING PROCESSES ON THE LUNAR SURFACE: STRATIGRAPHY OF THE LUNAR SURFACE POWDER NEAR SURVEYOR 1	27
V.	OTHER SPUTTERING EFFECTS ON THE MOON'S SURFACE	30
	A. Cementation of a Surface Powder	30
	B. Sealing of Exposed Pores	32
	C. The Question of Widespread Luminescence on the Moon	34
	D. Formation of H <sub>2</sub> O Due to Hydrogen Ion Bombardment of Oxides	39
VI.	ACKNOWLEDGEMENTS	42
VII.	LIST OF REFERENCES	43

## ABSTRACT

Research from 1963 to 1967 on effects of solar-wind bombardment of the lunar surface is summarized. Erosion due to sputtering by the solar wind is now estimated to be 2 cm in a  $4.5 \times 10^9$  yr history at current rates. Studies on lunar optical properties in comparison with ion-bombarded powder samples imply a low density surface of insulating (non-metallic) particles mostly less than 0.1 mm in diameter. Surveyor photographs are consistent with formation of a powder layer of at least meter thickness by meteoritic bombardment. Albedo contrast between rocks and powder in that layer is consistent with darkening of the powder by the solar wind or some other external agent or with marked differences in two rock sources contributing to that layer. Cementation of the lunar surface powder, now confirmed by Surveyor data, was suggested by cementation of ion-bombarded powder samples in simulation experiments. The observability of solar-wind erosion effects such as partial obliteration of surface pores is estimated to be difficult due to the presence of meteorite erosion at a rate one to three orders of magnitude faster. Luminescence on the moon due to the solar wind is discounted, though aurora-like excitation of the surface by electrons is considered marginally observable provided an efficient luminophor is the main constituent in the lunar surface layer in spite of the degrading effects of solar wind ion bombardment. Formation of  $H_2O$  due to hydrogen ion bombardment of oxides was investigated and shown to

proceed at about  $1 \text{ H}_2\text{O}/\text{H}_2^+$  on CuO powder. Studies of  $\text{H}_2\text{O}$  formation on powders where chemical effects are not expected are thus far inconclusive.

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I. INTRODUCTION

This report summarizes our research on solar-wind bombardment of the lunar surface for the past four-year period. The 15 Quarterly Reports<sup>(1-15)</sup> give extensive data and/or discussion of data pertaining to solar-wind effects on the moon. Below is a list of subjects treated in those reports to aid the reader in locating the more complete information. Then we discuss conclusions from these data (and a few new data) in an attempt to assess our current knowledge concerning interaction of the solar wind and the lunar surface.

Since physical sputtering yields differ for various materials by not more than one order of magnitude, erosion due to the solar wind could be estimated<sup>(16)</sup> without detailed knowledge of the lunar surface composition. We will give an updated estimate incorporating more recent experimental results on the effects of non-normal ion incidence and of surface roughness. Comparisons between the optical properties of the moon and of ion bombarded laboratory samples continue to be an important source of information. A paper which was submitted for publication to Journal of Geophysical Research on this subject will be outlined. Optical properties of the moon measured from earth average over large areas but Surveyor and Orbiter data now permit more detailed considerations of solar-wind effects. In another paper which

has been submitted for publication to "Science" we discuss albedo contrasts in relation to darkening of surfaces by the solar wind. We took into account active erosion of rocks and rock fragments by impacting meteorites. Other subjects we studied at least qualitatively include cementation of a surface soil, sealing of exposed pores, the question of widespread luminescence of the lunar surface, and formation of  $H_2O$  due to hydrogen ion bombardment of oxides.

#### Summary of Previous Reports

Report 1) A dish filled with small steel balls was dc sputtered by Hg ions. Strong cementation and weak growth of spires were noted. Powders of compounds were rf sputtered by Hg ions ( $Al_2O_3$ , CuO,  $Cu_2O$ , FeO,  $Fe_2O_3$ ) and by  $H_2$  ions ( $Cu_2O$ ). Weak cementation, darkening, and strong growth of spires were noted. Surface appearance changes indicated loss of oxygen from oxide powders (metal enrichment). Sample temperature was shown to be less than  $330^\circ C$ .

Report 2) X-ray analysis confirmed metal enrichment in ion bombarded CuO,  $Cu_2O$ ,  $Fe_2O_3$ ; no composition change could be detected on sputtered solid basalt, pumice, scoria. Photometer was described. White light photometry  $B(i, \epsilon)$  reported for sand, and for sputtered and unsputtered powders of  $Cu_2O$  and "basalt" (identified as greenstone in ref. 6). Electrical conductivity measured on CuO and  $Cu_2O$  after bombardment in Hg or  $H_2$ . Buildup of a crust cemented together by ion

bombardment for Hg ions on  $\text{Cu}_2\text{O}$  was observed. Sputtering yields were shown to depend on angle of incidence  $\theta$  roughly as  $\sec \theta$  for multi-keV  $\text{H}_2^+$  and  $\text{H}_3^+$  ions incident on Fe, Ni, and Au.

Report 3) Photometry of "basalt" as a function of exposure to  $\text{H}_2$  plasma or to  $\text{H}_2$  ions: darkening in either case, but much greater after ion bombardment. Photometry of solid scoria and pumice excludes such surfaces as important lunar surface component. Sputtering yields were measured at normal incidence for  $\text{H}_2^+$  and  $\text{H}_3^+$  ions of about 7 keV striking the oxides  $\text{TiO}_2$ ,  $\text{Fe}_2\text{O}_3$ , or  $\text{Al}_2\text{O}_3$ .

Report 4) Sputtering yields measured at normal incidence for oxides of Ti, Fe, or Al due to  $\text{He}^+$  and  $\text{H}^+$ . Darkening of "basalt" shown to be similar and pronounced after bombardment by ions of  $\text{H}_2$ , He, or  $\text{H}_2$ -He mixture but shown to be slight (moderate) after plasma exposure without enforced bombardment in He ( $\text{H}_2$ ). Photometry of solid surfaces of Holbrook and Bruderheim chondritic meteorites as a function of  $\text{H}_2$  ion dose. Summary of photometry in white light.

Report 5) Photometry in red and ultraviolet light for fine powders of 6 rock types for which also normal albedos in ultraviolet, green, and red light were measured for ion bombarded and unbombarded samples. Description of polarimeter.

Report 6) Three-color photometry and green-light polarimetry for sifted 0-20 $\mu$  samples of 6 rock types subjected to ion bombardments of up to  $10^5$  equiv. yr. on the moon. Darkening of sifted samples noted to be slower than for poured samples. Green-light polarimetry of 25-125 $\mu$  Fe powder and of solid surfaces of ion bombarded Holbrock meteorite, pumice, and scoria. Description of the preparation of "scraped", "poured", and "sifted" powder samples. Summary of maximum polarizations  $P_+$  and normal albedos  $A_n$  for powder samples and lunar features. Reprint of paper, "Darkening of powdered 'basalt' by simulated solar-wind bombardment". (17)

Report 7) Photometry and polarimetry as above for sifted samples of tholeiitic basalt and granodiorite in size ranges 20-44, 44-74, and 74-300 $\mu$ . Polarimetry in ultraviolet, blue, green, and red light on sputtered samples of granodiorite, 0-20 and 20-44 $\mu$ . Fine structure in polarization as a function of phase angle noted. Additional study of  $P_+$ - $A_n$  values in relation to particle size. Model for polarization at small phase angles discussed (later discounted).

Report 8) Photometry and polarimetry as above for sifted samples of greenstone and tektite in size ranges 0-20, 20-44, 44-74, 74-300 $\mu$ . Instrumental asymmetry in polarimetry noted. Angular fine structure in polarimetry related to reflection from groups of facets. Additional study of  $P_+$ - $A_n$  values using logarithmic coordinates. Effect of particle opacity noted on  $P_+$ - $A_n$  relationship at a given particle size. Tables



of  $P_+ - A_n$  for basalt, granodiorite, greenstone, and tektite plus lunar features. Introduction of a second parameter of polarization of scattered light: slope  $h$  of the degree of polarization curve for phase angles from  $20^\circ$  to  $60^\circ$ . Values of  $h$  derived from polarization data of Gehrels et al.<sup>(18)</sup> Discussion of additional polarization data from the literature.

Report 9) A ten-point summary of results to that time was given. Experiments on porosity changes of porous glass due to hydrogen ion bombardment were inconclusive. The compounds  $MgO$ ,  $CaO$ , and  $SiC$  were bombarded in hydrogen.  $SiC$  was the first substance for which the albedo increased under ion bombardment. Duoplasmatron beam facility described. Darkening experiment with non-mass-analyzed beam of  $H_3^+$  revealed much less darkening of basalt at all wavelengths than from comparable doses of ions from hydrogen plasma.

Report 10) X-ray analyses failed to show chemical changes in  $MgO$ ,  $CaO$ , and  $SiC$  due to hydrogen ion bombardment. Experiments revealed degrading of the luminophors  $(Zn, Cd)S:Ag$  and uranium glass by hydrogen ion bombardment and near-ultraviolet irradiation. Porosity changes in porous nickel were studied in argon. The representation of color differences in black and white photographs was studied. The small range of lunar colors was reviewed and compared to the wide range of colors observed in our powder samples before or after ion bombardment.

Report 11) Discussion of results obtained from Luna 9. Discussion of the evidences for a tenuous lunar surface layer. Additional experiments on the effect of surface roughness on the net sputtering yield from a surface. Chemical sputtering of carbon by hydrogen ions measured. Description of experimental equipment to study  $H_2O$  formation in hydrogen bombardment of oxides. A new method of analysis of photometric data was applied to our data and to data published by Gehrels et al.<sup>(18)</sup> on lunar features and by Rougier<sup>(19)</sup> on the whole moon. The method follows Hapke's<sup>(20)</sup> suggested factorization of the lunar photometric function into a Lommel-Seeliger function and an additional function depending on phase angle alone.

Report 12) Experiments on porosity changes in ion-bombarded rocks were inconclusive. Summary of optical effects on powders in solar-wind simulation experiments in comparison to lunar optical properties: equipment and procedure and criticisms thereof; dependence on composition (albedo, color); dependence on surface structure (polarization near quadrature, the Lommel-Seeliger factor in photometry, the steepness of the backscatter factor in photometry, a color-phase relationship, the opposition effect, backscatter of polarized light); dependence on particle size (polarization as a function of albedo and particle size).

Report 13) Buildup of a crust cemented by Hg ion bombardment: a column of Cu particles with steep sides obtained under dc bombardment; chains of Cu particles formed under rf bombardment; attempts to sputter

insulators under dc conditions; the importance of a returning flux of sputtered atoms in  $\text{Al}_2\text{O}_3$  crusting. Studies of  $\text{H}_2\text{O}$  formation in  $\text{H}_2$  ion bombardment of oxides (basalt): procedure with cold trap, surprising result of active  $\text{H}_2$  sorption, experimental difficulty of thermal  $\text{H}_2\text{O}$  desorption from sample, volatilization of carbon by chemical sputtering by hydrogen. Carbon and heavier elements in the solar wind: sputtering contribution estimated to be small relative to sputtering by helium, implantation of 450 km/sec carbon ions in  $\text{SiO}_2$  estimated in the presence of active sputtering by helium.

Report 14) Interpretation of high albedo rocks and low albedo powder near Surveyor 1 in terms of active powder formation by meteoritic erosion of lunar rocks and an exogenic darkening process. The alternative of a bleaching process. Extension to mare-highland albedo contrast. Discussion of powder darkening experiments of Nash<sup>(21)</sup> and of Greer and Hapke<sup>(22)</sup> which indicated evidences for involvement of carbon in darkening of powders in solar-wind simulation experiments. We showed the adequacy of the carbon source for their observed carbon. We argued for the relevance of catalysis in darkening effects due to carbon. Discussion of the similarity to the lunar case and the open question of darkening by carbon or metal enrichment. Re-interpretation of lunar and laboratory photometric data showing that a Lommel-Seeliger factor in the lunar photometric function is merely an approximation valid at moderate phase angles. The lunar photometric function

and multiple scattering: color dependence on phase angle  $\alpha$  at moderate  $\alpha$  (red, gray, and blue powders) and at small  $\alpha$  (opposition effect for Saturn's rings, the moon, and asteroids).

Report 15) Preprint of paper submitted for publication in "Science" interpreting albedo contrasts near Surveyor 1 as above, but deleting the possibility of bleaching of rock surfaces (no plausible mechanism). The alternative of two kinds of rock material near Surveyor 1.

## II. EROSION RATES DUE TO PHYSICAL SPUTTERING BY THE SOLAR WIND

Our early estimate<sup>(16)</sup> of the erosion rate for the moon and other interplanetary objects not protected by an atmosphere was based on preliminary data on solar-wind fluxes and energies and on sketchy sputtering yield data at normal and non-normal angles of incidence. The erosion rate must now be revised down by about an order of magnitude because (a) the helium/hydrogen ratio is smaller than was expected from abundance estimates, (b) the quiet solar wind is slightly less energetic than was estimated, (c) the increase in sputtering by light ions incident at angle  $\theta$  to the surface normal is cancelled by the  $\cos \theta$  decrease in ion current density, and (d) extreme surface roughness seems capable of reducing net sputtering yields by a larger factor relative to a smooth surface than we estimated. In the case of bodies as large as the moon, additional consideration must be given to collective phenomena in the solar wind which might lead to partial (and differential) deflection of the ions around the body. Also consideration should be given to gravitational retention and redeposition of part of the sputtered atoms. However, no improvement in our knowledge of these latter subjects has been achieved so we assume undeviated flow of the plasma to the moon and total escape of the sputtered atoms from the moon for the purposes of this discussion.

At this time the most complete analysis of an interplanetary plasma experiment is that for Mariner 2 by Neugebauer and Snyder.<sup>(23)</sup> Additional data are available from Pioneer 6<sup>(24-26)</sup> and Explorer 18,<sup>(27)</sup>

which confirm the Mariner 2 values in a semi-quantitative way. The average proton density is about  $5 \text{ cm}^{-3}$  and the average velocity is about 500 km/sec (1.3 keV). Because of the interplanetary magnetic field, the helium ions  $\text{He}^{2+}$  and  $\text{He}^+$  are expected to have the same velocity as protons. They may therefore be detected in the electrostatic plasma analyzers that sort particles according to energy per unit charge, provided the dispersion in proton velocities is not too great. Generally, this limits helium detection to quiet, low-velocity conditions. The Mariner 2 data give  $\text{He}^{2+}/\text{H}^+ \approx 0.046 \pm 0.038$ , which is to be compared to  $0.095 (\pm 40\%)$  from a combination of solar cosmic-ray and spectroscopic data.<sup>(28)</sup> Neugebauer and Snyder point out that their low  $\text{He}^{2+}/\text{H}^+$  ratio represents quiet conditions and that the ratio may be higher under the more energetic, disturbed conditions. Our previously adopted  $\text{He}^{2+}/\text{H}^+$  ratio of 0.15 was a compromise between values between 0.1 and 0.2 that are derived from cosmogenic abundance data.

Simple hydrodynamic and evaporative models of the solar wind predict a significant decrease in the abundance of heavy elements in the solar wind if the coronal abundances are taken to be the photospheric abundances. The close relationship of such models has been reviewed by Lemaire.<sup>(29)</sup> But recent measurements of coronal abundances<sup>(30)</sup> have indicated enhancements of heavy elements in the corona. Therefore Brandt<sup>(31)</sup> coupled this observation with his realization that the entire corona has to be replenished in a short time equal to some weeks and suggested that the abundances in the solar wind by flux should equal the photospheric abundances. On the other hand, helium is a difficult

case because its abundance influences the temperature required for the support of the corona and, in turn, the transport conditions.

Even though helium is a minor constituent in the solar wind, sputtering by helium is very important because sputtering yields expressed in atoms eroded per ion are characteristically an order of magnitude larger for helium than for hydrogen. We therefore must consider the helium flux very carefully. We adopt the view that low helium fluxes are indeed realized in quiet solar wind conditions and accept a value of  $\text{He}^{2+}/\text{H}^+ = 0.05$  as given by the several plasma experiments. But we feel that the most conservative view is to adopt  $\text{He}^{2+}/\text{H}^+ = 0.1$  during solar storms. Fortunately, the final erosion rate is not sensitive to the latter choice because of the short duration of disturbed conditions.

Plasma velocities from 400 to 800 km/sec are commonly reported in the interplanetary plasma experiments. According to a large number of data obtained by us for hydrogen and helium ions incident on 19 metals,<sup>(32)</sup> this range of ion velocities is accompanied by marked changes in sputtering yields. A similar situation should hold for the alumino ferromagnesian silicates usually assumed on the surfaces of natural planetary objects. But two features cooperate to simplify the situation. Except for the metals Cu, Ag, Au which have the highest sputtering yields and which achieve a maximum sputtering yield in this ion velocity range, our data indicate that most of the sputtering yields increase nearly linearly with energy in this velocity range. Second,

the Mariner 2 data<sup>(23)</sup> show that proton density  $n_p$  and plasma velocity  $v$  are correlated inversely:  $n_p v^3 \cong \text{constant}$ . But the erosion rate due to sputtering is also proportional to  $n_p v^3$  when the sputtering yield is proportional to ion energy. Then it is sufficient to use average values of  $n_p$  and  $v$  in estimating erosion due to the (nearly) quiet solar wind. The estimate so obtained may be a slight overestimate if the sputtering yield falls below a linear increase with ion energy at the higher ion energies.

A few sputtering yields were measured for oxides bombarded by hydrogen and helium ions using mass-analyzed beams to drill holes through thin foils.<sup>(3,4)</sup> The foils were prepared by pressing oxide powders or by oxidizing metal foils in air at elevated temperatures. Sputtering yields for  $\text{He}^+$  were obtained at 5, 7, and 9 keV usually. Our best estimate of the yield at 6 keV is given in Table IA. Sputtering yields for  $\text{H}_2^+$  and  $\text{H}_3^+$  were obtained at 7 keV. Our experience with various metals shows that each of the atoms in a molecular hydrogen ion sputters independently (i.e.,  $\text{H}_2^+$  sputters like two  $\text{H}^+$  incident separately at the same speed). Therefore proton sputtering yields at 2.3 and 3.5 keV follow from the  $\text{H}_3^+$  and  $\text{H}_2^+$  sputtering yields at 7 keV, respectively. Interpolating to 3 keV, our best estimates of proton sputtering yields at 3 keV on metal oxides are given in Table IA. The proton sputtering yields are of the order of  $10^{-2}$  molecules/ion, where the molecule is taken to contain just one metal atom. For helium the yields on metal oxides are an order of



Table I. Estimates of sputtering yields appropriate to solar-wind ions

A. Sputtering yields for 3 keV  $H^+$  or 6 keV  $He^+$  at normal incidence

<u>Substance</u>	<u><math>Y_H</math> (mol/ion)</u>	<u><math>Y_{He}</math> (mol/ion)</u>
MgO	$12 \times 10^{-3}$	---
$AlO_{1.5}$	$5 \times 10^{-3}$	$60 \times 10^{-3}$
$SiO_2$	$35 \times 10^{-3}$ *	---
$TiO_2$	---	$27 \times 10^{-3}$
$FeO_{1.5}$	$5 \times 10^{-3}$	$80 \times 10^{-3}$
Fe	$11 \times 10^{-3}$	$115 \times 10^{-3}$

\*May be overestimated by a factor of two. Other values are probably uncertain by at least 20%.

B. Sputtering yields for  $H^+$  and  $He^{2+}$  normally incident on Fe at quiet solar wind and solar storm speeds

<u>Ion</u>	<u>Condition</u>	<u>Energy (keV)</u>	<u>Sputtering Yield (atom/ion)</u>
$H^+$	quiet	1.25	0.0045
$H^+$	storm	5.0	0.012
$He^{2+}$	quiet	5.0	0.10
$He^{2+}$	storm	20	0.06

magnitude larger, a general feature also established<sup>(32)</sup> for 8 metals for which sufficient yield data were obtained. According to a sputtering theory by Rol<sup>(33-36)</sup> for light ions incident on heavy-atom solids, the sputtering yields for 3 keV  $H^+$  and 6 keV  $He^+$  may be directly compared without knowing the interatomic potentials in great detail. The ratio of sputtering yields should be 8, whereas we found approximately 10. The oxide sputtering yields are uncertain by at least 20% (compared to about 5% for the metals), but this feature is apparently true for oxides also. We conclude that the presence of oxygen does not change the main features of sputtering by hydrogen and helium ions. We therefore use sputtering data on metals as a guide to sputtering yield behavior on metal oxides.

Further evidence on metal oxide sputtering by hydrogen and helium is afforded by a comparison of metal and metal oxide yields for a given ion at the same ion energy.<sup>(3,4)</sup> For Al, Ti, and Fe the corresponding metal oxide yields are lower than the metal yields by a factor of 2 to 3 for either hydrogen or helium. This suggests that the presence of the oxygen decreases the sputtering yield by merely requiring that an additional atom or two be dislodged per metal atom that is sputtered free. For Si our data indicated that the oxide yield for hydrogen was as large or, perhaps, twice as large as the Si yield. Unfortunately, only three runs were made because of experimental difficulties with the ion source that began at that time. No helium yields were obtained. Therefore we are especially

uncertain about the sputtering yield of the important Si-SiO<sub>2</sub> system. We prefer  $Y_H(3 \text{ keV}) \approx 18 \times 10^{-3} \text{ mol/ion}$  for either Si or SiO<sub>2</sub>.

In view of the uncertainties in the data of Table IA and in the lunar surface composition, we believe the sputtering yield of Fe is the best estimate for the sputtering yield on the mixed composition that must occur on the lunar surface. Therefore in Table IB we give sputtering yields of Fe at the ion energies appropriate to the quiet solar wind and to solar storms. This procedure is in accordance with our previous estimate,<sup>(16)</sup> where we also presented evidence that similar erosion rates occurred on Fe and various rock materials when the eroding ion was Hg<sup>+</sup>.

In Table II we summarize our former and present estimates of sputtering rates due to the solar wind. Note that no corrections have been incorporated in Table II for the effects of non-normal incidence, rough surfaces, day-night, etc. The main changes are in the quiet solar wind plasma velocity (which in turn alters the sputtering yield) and the decreased helium flux in the quiet solar wind. Slight changes in the sputtering yields have arisen from the advent of better data in addition to the changes arising from different ion energies. For solar storms we again adopt a tenfold increase in flux for 1/60 of the time at 1000 km/sec. The former erosion rate on smooth Fe normal to the full plasma flow was  $1.2 \text{ } \overset{\circ}{\text{A}}/\text{yr}$  and is here estimated to be  $0.25 \text{ } \overset{\circ}{\text{A}}/\text{yr}$ . Note that sputtering is now about equally due to hydrogen and helium due to the decreased helium flux. Storms account for only about 1/5 of the erosion because

Table II. Estimates of sputtering rates due to the solar wind

A. Former estimate<sup>(16)</sup>

<u>Ion</u>	<u>Flux</u>	<u>Velocity</u>	<u>Energy</u>	Yield (atoms/ion) for Normal Incidence, <u>Smooth Surface</u>		Sputtering Rate (atom/cm <sup>2</sup> yr)
Proton (quiet wind)	2x10 <sup>8</sup> /cm <sup>2</sup> sec	600 km/sec	1.85 keV	Fe	0.009	0.57x10 <sup>14</sup>
				Stone	0.009	0.57x10 <sup>14</sup>
Proton (solar storm)	20x10 <sup>8</sup> /cm <sup>2</sup> sec for 1/60 of time	1000 km/sec	5.0 keV	Fe	0.008	0.08x10 <sup>14</sup>
				Stone	0.008	0.08x10 <sup>14</sup>
α-particle (quiet wind)	0.3x10 <sup>8</sup> /cm <sup>2</sup> sec	600 km/sec	7.4 keV	Fe	0.25	2.4x10 <sup>14</sup> *
				Stone	0.29	2.7x10 <sup>14</sup> *
α-particle (solar storm)	3x10 <sup>8</sup> /cm <sup>2</sup> sec for 1/60 of time	1000 km/sec	20 keV	Fe	0.06	0.95x10 <sup>14</sup>
				Stone	0.07	1.1x10 <sup>14</sup>

Totals:	Fe	4.0x10 <sup>14</sup>
*Corrected for arithmetic error.	Stone	4.4x10 <sup>14</sup>

B. Present estimate

Proton (quiet wind)	2.2x10 <sup>8</sup> /cm <sup>2</sup> sec	500 km/sec	1.25 keV	Fe	0.0045	0.31x10 <sup>14</sup>
Proton (solar storm)	20x10 <sup>8</sup> /cm <sup>2</sup> sec for 1/60 of time	1000 km/sec	5.0 keV	Fe	0.012	0.13x10 <sup>14</sup>
α-particle (quiet wind)	0.11x10 <sup>8</sup> /cm <sup>2</sup> sec	500 km/sec	5.0 keV	Fe	0.10	0.35x10 <sup>14</sup>
α-particle (solar storm)	2x10 <sup>8</sup> /cm <sup>2</sup> sec for 1/60 of time	1000 km/sec	20 keV	Fe	0.06	0.06x10 <sup>14</sup>
					Total	0.85x10 <sup>14</sup>

sputtering yields are falling below a linear increase at the higher energies.

We performed special experiments to investigate the erosion rate of smooth metal surfaces due to ions at non-normal incidence.<sup>(2)</sup> According to Rol<sup>(33-36)</sup> and in similar theories<sup>(37)</sup> in which the sputtering yield is proportional to the probability that a strong scattering event takes place within a certain distance from the surface, the sputtering yield is proportional to  $\sec \theta$ , where  $\theta$  is the angle of incidence. On a wire of circular cross section in a rectilinear beam of ions, the erosion rate in the radial direction should then be constant over the half of the wire being bombarded by ions because the  $\cos \theta$  decrease in ion current density cancels the  $\sec \theta$  increase in sputtering yield at oblique incidence. In that case erosion should maintain a circular profile on the eroded surface. For wires of Fe, Ni, and Au bombarded in beams of 6 to 8 keV  $H_2^+$  or  $H_3^+$  ions, these expectations were confirmed. This situation is different for heavy ions where yields at oblique incidence increase more rapidly than  $\sec \theta$ . We consider the situation on the moon and smaller interplanetary bodies to be completely analogous to the wire in a  $H_2^+$  beam if the solar wind ions are not deviated during approach to the body.

In case the bombarded surface is rough, two additional considerations apply. Some portions of the surface are shadowed at oblique incidence; those that are irradiated tend to be sloped toward the source of ions relative to the local mean surface. Therefore positive relief

features tend to be eroded preferentially but the net radial erosion rate is somewhat less than at an area where incidence is normal because  $\sec \theta \cdot \cos \bar{\theta} < 1$ . We could see this experimentally at the limits of the ion erosion region where the tangent to the profile of the wire assumed a finite angle to the beam direction while theory required that the tangent approach the beam direction where  $\bar{\theta} = 90^\circ$ . For the moon we consider this roughness effect a correction of second order as it applies only near the terminator at any given moment. But second, in a multiply-connected surface like a powder or even in a surface having grooves or pits, atoms sputtered from positions below the mean surface have a decreased probability of escaping from the mean surface owing to decreased open solid angle. Many atoms stick on a nearby projection. On metals with threaded surfaces we demonstrated<sup>(16)</sup> decreases in the net sputtering yield amounting to a factor of 2. In experiments with an assembly of sewing needles<sup>(11)</sup> we found a decrease as great as a factor of 3. The net sputtering yield on an underdense powder (which seems to be general on the moon) may be less than 1/3 the rate of a smooth rock of the same substance. We adopt a correction to the net erosion rate of 1/3 in preference to the former estimate<sup>(16)</sup> of 1/2.

Finally, in summary, we estimate an erosion rate of  $0.25 \text{ } \overset{\circ}{\text{A}}/\text{yr}$  due to the full solar wind striking a smooth Fe or stony surface and we correct by a factor  $\sec \theta$  for increased sputtering yields at oblique incidence,  $\cos \theta$  for decreased current density at oblique incidence,

$1/3$  for roughness of the lunar surface, and  $1/2$  for lunar night. The net erosion rate is then  $0.042 \text{ \AA/yr}$  or  $0.42 \text{ cm}/10^9 \text{ yr}$ . In  $4.5 \times 10^9 \text{ yr}$  the net erosion is about 2 cm. The net erosion may be somewhat less if some of the solar wind ions are deflected around the moon and if some of the sputtered atoms are retained by the lunar gravitational field.

### III. OPTICAL PROPERTIES OF THE MOON AND OF LABORATORY SAMPLES

In this section we summarize briefly the results of optical studies we made<sup>(2-14)</sup> on unbombarded and bombarded laboratory samples, mostly powder samples, and evaluate the results in comparison to results obtained from astronomical studies on the moon. More detail will be given in a paper due to be published in the Journal of Geophysical Research on 15 June 1967. Reprints will be mailed to those receiving this Final Report as soon as available. The title and abstract are as follows:

#### Parameters of the Optical Properties of the Lunar Surface Powder in Relation to Solar-Wind Bombardment

#### ABSTRACT

The optical properties of the moon are quantitatively compared with those of powder samples bombarded by ions from a hydrogen discharge plasma. Deficiencies in the simulation of the solar-wind bombardment include contaminants deposited on and injected into the sample surface. Also an unknown fraction of the sputtered atoms returns to the lunar surface after flight in the gravity field. The variable albedo of the powder samples due to darkening by ion bombardment is studied in relation to parameters of color, photometric function, and polarization while holding composition, surface structure, or powder particle size fixed. Simulation of the solar wind was not adequate to permit identification of lunar compositions from lunar color. The lunar photometric function requires a rough macrostructure.



But a number of properties of the photometric function plus the polarization of earthshine are shown to be incapable of presently proving whether the lunar surface is underdense or compacted. A polarization parameter indicates a lunar powder whose particles are mostly less than 0.1 mm in size. Effects expected from solar-wind bombardment include surface darkening and decoloration, erosion, preferential erosion of some substances, dust cementation, and alterations of surface layer composition.

Sunlight scattered from the earth and falling on the moon is in general polarized and the portion of this light that is scattered back toward the earth ("earthshine") is also polarized, though to a lesser extent. The ratio of outgoing to ingoing polarization  $R$  depends upon the normal albedo  $A_n$  and optical conductivity of the scattering surface but very little on surface compaction or particle size (in the range we have studied). The dependence of  $R$  upon  $A_n$  is substantially a power-law relationship for insulators,  $RA^{0.6} \approx \text{constant}$ . Lunar values are in good agreement with those for insulating powders in that the returning polarization is low. For metals and even for semiconductors like Si and Ge the returning polarization would be far higher so we concluded that the lunar surface is not appreciably enriched in free metal. Enrichment in metal was a distinct possibility because experiments with powders of the oxides of copper and iron which were sputtered by hydrogen, argon, or mercury ions showed that oxygen was preferentially removed until the

surface was substantially metallic. In fact, in the experiments with argon, oxygen was present as an impurity in the argon at the  $10^{-4}$  level but the reduction proceeded nevertheless.

Sunlight scattered from the moon becomes slightly polarized, though far less than would be expected for a random assemblage of rocks of centimeter dimension or larger. The polarization depends upon albedo, optical conductivity, and, for powders in which the particle diameter is less than about a millimeter, upon particle size and opacity and upon powder compaction. The question of metallizing is settled by the polarization of earthshine. Photometry cited below calls for minimal compaction in an ubiquitous powder on the moon. The albedo of rock powders was a variable that could be decreased at will by ion bombardment in a hydrogen plasma without a metal enrichment that would be in variance with earthshine data. The uncertain parameters remaining were the particle size and opacity so the possibility existed for an indirect determination of the particle size in the lunar surface layer. The result was that an important particle size in that layer is 0.1 mm for translucent grains, 0.05 mm for opaque grains. Smaller particles make little contribution to the polarization so the determination is heavily weighted in favor of the largest particles.

Regions of the moon within about  $60^\circ$  of the subearth point have a brightness governed quite accurately by a relation of the form  $I(i, \epsilon, \alpha; \lambda) = L(i, \epsilon)F(\alpha; \lambda)$  for light of wavelength  $\lambda$ , where  $i$  and  $\epsilon$  are the angles of incidence and emergence with respect to the average surface

normal in a resolved area and  $\alpha$  is the phase angle sun-lunar feature-observer.  $L(i, \epsilon)$  is the Lommel-Seeliger function  $L(i, \epsilon) = (1 + \cos \epsilon \sec i)^{-1}$  which arises naturally for cases where light is absorbed exponentially with path length in a medium. Removal of this gross dependence on the angles of incidence and emergence from the lunar photometric observations permitted detailed study of the remaining dependence on phase angle and wavelength for a number of lunar features. The function  $F(\alpha; \lambda)$  exhibited little variation in 11 varied lunar features.

The function  $F(\alpha; \lambda)$  in a theory due to Hapke<sup>(20)</sup> is separable into  $a(\lambda) \cdot S(\alpha) \cdot B(\alpha)$ , where  $a(\lambda)$  is the reflectivity of scattering particles which have an average scattering function  $S(\alpha)$ . The function  $B(\alpha)$  described the collective effects of shadows in a porous assembly of scatterers. The function  $S(\alpha)$  varies slowly as a function of  $\alpha$  near  $\alpha = 0$  (full moon conditions) whereas  $F(\alpha; \lambda)$  is experimentally found to vary rapidly so shadowing effects described by  $B(\alpha)$  are important on the moon. Therefore  $F(\alpha; \lambda)$  contains information on powder compaction.

We gave evidence however that  $F(\alpha; \lambda)$  is not fully described by the product function proposed by Hapke because multiple scattering was not taken into account. In particular, Hapke's product function predicted that the angular dependence of the brightness is independent of the wavelength of scattered light, i.e., the color of the moon would not depend on the time of the month at which it is measured. In fact, a small dependence upon phase angle of the color of the slightly reddish moon and of similarly reddish powders was established. This angular

dependence of the brightness was found to be independent of the wavelength for gray powders ( $a(\lambda) = \text{constant}$ ), even for powders having very small particles, so diffraction is not contributing an explicit wavelength dependence through, say,  $S(\alpha; \lambda)$ . Second, Hapke's product function fails to predict an abrupt change in the angular dependence of the brightness at a phase angle of about  $5^\circ$ . A marked angular dependence of the color is associated with this "opposition effect" in laboratory powders and in scattering from Saturn's rings. We suggested that the abrupt change in the slope of the brightness-phase angle curve for the moon is a second effect due to multiple scattering. In this case one of the scatterings apparently involves glancing incidence and emergence from a dielectric surface in a powder structure.

Nevertheless, the lunar albedos are so low ( $<20\%$ ) that multiple scattering must be small at phase angles larger than about  $5^\circ$ . Therefore, the steepness of the decrease of  $F(\alpha; \lambda)$  with increasing  $\alpha$  must contain some information on powder compaction. First, though, the angular dependence of scattering from an average particle must be briefly considered. We showed that the occurrence or development of large facets on powder particles resulted in a less steep decrease of  $F(\alpha; \lambda)$ , i.e., the scattering was more diffuse. Faceted opaque particles have an average phase function  $S(\alpha)$  approaching  $\cos \alpha/2$ , which decreases less steeply from  $S(0) = 1$  than the phase function proposed by Hapke<sup>(20)</sup> for rough opaque particles (see Table 31 of Harris<sup>(38)</sup> for the values of the phase function of a particle scattering according to Lambert's

law). Therefore an ambiguity about powder compaction will exist unless the presence or absence of marked faceting of the lunar powder particles can be established. We found marked faceting arises in breaking rock materials into a powder and in sputtering of powders with ions incident from one direction only. Whether sputtering causes facet growth when ions are incident from a range of directions will be the subject of future research. On the other hand, possibly rough scatterers arise naturally in spite of faceting when small (faceted) particles stick to and coat large (faceted) particles. We therefore feel uncertain about the role of facets on the scattering functions of particles and only remark that faceted particles would have to be less compacted than rough particles in order to agree with photometry of the moon.

For almost all the powders studied photometrically by us, the decrease of  $F(\alpha; \lambda)$  as  $\alpha$  increases was less steep than for the moon. Agreement improved when ion bombardment caused the albedo to be decreased into the range of lunar albedos. Agreement improved further when compaction of the powder was minimized. But one powder, greenstone, was reported in the paper to exceed the moon in steepness of decrease of  $F(\alpha; \lambda)$  even if powder compaction was not minimal. Further data obtained by refined photometric techniques and equipment do not confirm this very steep decrease for greenstone but do indicate that agreement with the moon occurs for greenstone powder when the albedo is adequately low and the compaction is minimized. Adequately low densities required particles less than  $20 \mu$  in diameter for the magnitude

of interparticle forces experienced at atmospheric conditions and for terrestrial gravity. Presumably somewhat larger particles could be maintained in a similar underdense geometry under lunar conditions.<sup>(39)</sup> We conclude that lunar photometry implies a low density in the surface powder, approaching 80% void space (perhaps  $0.6 \text{ gm/cm}^3$ ).

The range of lunar colors is very narrow despite a range of normal albedos from 5% to 20% (in green light). Neither in our experiments with ion-bombarded terrestrial powders nor in others<sup>(40)</sup> has ion bombardment been shown to result in a narrow range of colors approximating that of the moon, though isolated instances of agreement have been found. The narrow range of lunar colors might imply a narrow range of lunar compositions, though this is unlikely if the moon was ever subject to volcanic activity capable of forming structures on the scale of the maria. We mentioned two alternatives in which exogenic influences mask composition differences superficially through a moon-wide homogenization process. Both atoms that are sputtered by the solar-wind ions<sup>(16)</sup> and some particles and vapor<sup>(41,42)</sup> that result from meteorite impact have velocities adequate to permit near circumlunar orbits. Such processes could not completely obliterate local composition differences giving rise to color contrasts involving sharp lines, such as have been established on the moon.<sup>(18,43)</sup> But they would subdue composition differences in an overlying layer.

#### IV. THE EXISTENCE OF DARKENING PROCESSES ON THE LUNAR SURFACE: STRATIGRAPHY OF THE LUNAR SURFACE POWDER NEAR SURVEYOR 1

A paper interpreting albedo contrasts observed in the Surveyor 1 photographs has been submitted to "Science" and is available in a Quarterly Report.<sup>(15)</sup> We outline it here.

#### ABSTRACT

Two hypotheses are examined to account for an abundant dark powder amidst high albedo rocks near Surveyor 1. Meteoritic bombardment is estimated to have been of primary importance in forming the powder. Darkening, including an observed increasing darkening with depth in the powder, could have resulted from an external influence. Alternatively, the powder may be largely derived from a rock species that is easily crushed to a dark powder. A model of solar-wind darkening and meteoritic mixing is discussed in relation to maria, ray craters, and highlands.

In Surveyor 1 photographs one sees a few objects which are resolvably angular. The larger objects are presumably rocks and have markedly higher albedos than the surrounding surface. The surface in turn had a higher albedo than material below the surface which was exposed by the motion of the spacecraft footpads during landing. More than about 90% of the undisturbed surface consisted of particles smaller than 1 mm in diameter. But since finely divided rock material

is ordinarily of higher albedo than the parent rock, the albedo contrasts in the photographs present a problem unless (a) there exists a darkening process consistent with the albedo contrasts or (b) the dark powder has a separate parentage.

We argued that if the powder were being dynamically derived from the visible (exposed) rocks and darkened whenever exposed at the surface, then rocks have the freshest surfaces visible (highest albedoes), the undisturbed surface is an intermediate mixture of fresh rock chips and older ones (intermediate albedo), and the sub-surface material is mostly old rock fragments (low albedo).

Certainly the size distribution of rock fragments in the photographs must be consistent with the above suggestion. In considering what size distribution might be expected in view of the size distribution in interplanetary particles, we found that our limited knowledge would permit a second explanation of the albedo contrasts. The size distribution of rock fragments from hypervelocity impacts can depend markedly on the size distribution of physically strong units (crystals or similar units) already existing in the rock. Therefore if two types of rock are present of which the abundant species has small dark crystals and the other has large high-albedo chunks, then the contrasts follow. As before, the undisturbed surface is an intermediate mixture of chips from the high albedo rocks and of the dark powder, but now darkening with depth proceeds by dilution. Concerning this view, however, we remarked that we would expect to see a few dark chunks somewhere on the surface. None was found in the limited sample.



Applied to other lunar areas, the alternatives of several compositions or of a single dominant composition being slightly modified in a darkening process again appear. The disappearance of crater "rays" could be caused by mixing light material into darker material or by darkening the surface exogenically. The high albedo of high-land areas might result from a dominance of high albedo rock (in powder form in the uppermost layer) or from the presence of a high albedo powder laid down in an ancient epoch of minor darkening effects and now occasionally exposed in the current erosion and mixing processes.

Chemical analysis of the surface rocks and powder would be decisive in rejecting one of the hypotheses for a particular lunar area. Also, if the dark powder were decisively proven to be mostly less than about  $20\ \mu$  in diameter, then only a darkening process could be admitted because we have found no rock material having an albedo in the lunar range and having such small particles.

## V. OTHER SPUTTERING EFFECTS ON THE MOON'S SURFACE

### A. Cementation of a Surface Powder

In view of a well-demonstrated tenuous surface layer on the moon,<sup>(11)</sup> mechanical properties of the lunar surface have been very uncertain. Suggestions of mechanisms involving external agents that tend to increase the coherency of the low density surface layer have included meteorite impact vaporization,<sup>(41)</sup> sputtering by the solar wind,<sup>(41,44)</sup> and sintering caused by crystal damage.<sup>(45)</sup> The effectiveness of these mechanisms is highly uncertain without detailed consideration of the competing crushing action of meteorite impacts and quantitative information on "cementing" rates.

In experiments conducted to assess cementing rates due to solar-wind sputtering, we found<sup>(13)</sup> that cementation by sputtering is made even more uncertain by our lack of knowledge of the velocities of atoms sputtered from complex solids by hydrogen and helium ions. A fraction (perhaps 1/3) of the atoms sputtered from lunar powder particles escape from the powder structure. If they do not escape from the moon, they contribute to additional cementation. But reliably known velocities of sputtered atoms are confined to metals<sup>(46,47)</sup> and then usually for bombardment by heavy ions. Copper atoms sputtered by helium ions were considerably slower than those sputtered by more massive ions of comparable energies<sup>(46)</sup> so that less than half of the former atoms exceeded

the lunar escape velocity. On likely lunar materials the escape of sputtered atoms (or possibly molecules) is apt to be selective by element so that simulation of a returning flux in the absence of velocity data would involve varying both magnitude of the returning flux and its composition. We found that a small returning flux caused a marked change in the cementation of  $\text{Al}_2\text{O}_3$  being bombarded by Hg ions. With no returning flux we found marked differences in the strength of a surface crust on different powder compositions. Generally, compositions that darkened readily (basalt, greenstone, obsidian) also formed stronger crusts than materials that darkened but little ( $\text{SiO}_2$ ,  $\text{Al}_2\text{O}_3$ ) for the same ion dose.

Since our cementation studies involved ion bombardment in a plasma, strong dc or rf fields existed at the sample surface. Conducting particles permitted dc bombardment but are of limited interest. Conducting particles in an rf ion sheath were found to be subject to large electro-mechanical forces<sup>(13)</sup> while insulating particles are subject to smaller forces. The latter forces were adequate to align surface particles, an effect that grew in importance if particles were rendered conducting by ion bombardment. Since we considered that samples built up from aligned particles would have spurious mechanical properties, we discontinued efforts to produce samples built up of ion-bombarded layers. Recently, the development of a new type of ion source promises to permit injection of an ion beam into a plasma such that sputtering may proceed in low-field conditions while returning fluxes are simulated.

## B. Sealing of Exposed Pores

In the process of sputtering a porous surface, some of the material sputtered from the sides of a hole will be transferred deeper into the hole and contribute to a decrease in permeability. We conducted permeability measurements to assess the changes in permeability that might result. In experiments with porous nickel bombarded by argon ions we found<sup>(10)</sup> that the removal by sputtering of a thickness equal to a mean pore size resulted in a permeability decrease of about 10% while simple deposition of such a thickness caused a 20% decrease. In sputtering there is a competition between the closing and opening of pores so that the smaller effect per unit thickness due to sputtering was qualitatively expected. In experiments with hydrogen ions we found<sup>(9,10)</sup> permeability increases which were apparently the consequence of chemical cleanup of pores.

The result of our above estimate of sputtering rates was  $0.125 \text{ } \overset{\circ}{\text{A}}/\text{yr}$ , omitting the correction for a rough surface, or  $12.5 \text{ } \mu/10^6 \text{ yr}$ . We consider here as an example whether partial obliteration of  $10\mu$  pores on an exposed "smooth" surface is apt to be observable, i.e., whether exposure times of the order of  $10^6 \text{ yr}$  are probable before obliteration of a surface by meteoritic impacts.

Several lines of evidence permit the erosion rate on the moon due to meteorites to be bracketed between  $10^{-2}$  and  $1 \text{ cm}/10^6 \text{ yr}$ . By erosion we mean disturbance by impact craters or ejecta. The higher limit is to be preferred on the basis of Jaffe's<sup>(48,49)</sup> assertion that a 5 to 10 m

granular layer has resulted from meteoritic bombardment of a region photographed by Ranger 7 which we may take to be  $10^9$  yr old for our purposes. The lower limit was suggested by Bastin<sup>(50)</sup> on the basis of a conservative estimate of the area covered by primary craters alone when meteorite flux rates at the moon are considered. Using his approximation to the meteorite flux rates and assuming cratering laws hold for projectiles smaller than a gram, he concludes small craters are dominant in importance in covering a unit area and that centimeter primary craters should cover any area in about  $10^7$  yr. Alexander and Bohn<sup>(42)</sup> considered that the number of meteorites smaller than about  $10^{-6}$  g fell below the estimate used by Bastin in order to give agreement with zodiacal light measurements and data from Mariners 2 and 4. But Bastin's conclusion would not be affected by this refinement for primary craters larger than about 1 mm in diameter.

We now make the point that any exposed surface on the moon should be completely covered by 1 mm diameter pits in about  $10^6$  yr if primary craters alone are considered and if a conservative primary meteorite flux is assumed. We conclude that partial obliteration of  $10\mu$  pores by solar-wind sputtering in  $10^6$  yr is apt to be difficult to observe in the presence of the stronger erosion due to micrometeorites. This conclusion is not apt to be sensitive to a change in the time scale and characteristic physical dimension by the same factor, even if they are varied over several orders of magnitude. This conclusion does not say that solar-wind sputtering will have no visible manifestation on the lunar surface but it does suggest that the "noise" level will be high.

### C. The Question of Widespread Luminescence on the Moon

Recent observations of the sunlit or eclipsed moon in which luminescence had been alleged to play a role were reviewed by Ney, Woolf, and Collins.<sup>(51)</sup> Older observations, including supposed outbursts on the side of the moon illuminated only by earthshine and other weaker light fluxes, have been reviewed by Burley and Middlehurst.<sup>(52)</sup> Ney et al. emphasize the absence of adequate energy in particle fluxes and the absence of variability in adequately energetic photon fluxes to account for the emissions in terms of direct processes involving the solid surface. They admit the possibility that thermoluminescence could conceivably account for the cited emissions but then the emissions would repeat regularly every month, which seems not to be so. Sun and Gonzalez<sup>(53)</sup> reported experiments on thermoluminescence of an enstatite achondrite meteorite which had been irradiated by 2 MeV electrons. Their interpretation in terms of solar-wind bombardment during the lunar night followed by warmup at eclipse rates leaves something to be desired, but additional experiments of this type are needed. Nash<sup>(54)</sup> and Schutten and van Dijk<sup>(55)</sup> showed that solar wind ion-induced luminescence of a silicate surface is certainly not involved because at the appropriate ion energies the luminescent efficiencies are very low, of the order of  $10^{-4}$  to  $10^{-6}$  photons/ion, and the solar-wind energy flux is at most already much smaller than the energy flux in moonlight. Middlehurst<sup>(56)</sup> also recognized the inadequacies of such energy sources and preferred the suggestion by Kozyrev<sup>(57)</sup> of massive gas emissions. However, no adequate description of the dynamics of such gas emissions has been worked out. In particular,

Kopal<sup>(58)</sup> rejects gas emission from the lunar interior as a possible explanation for the brightening which he reported<sup>(59)</sup> for a large area of the moon. We will conjecture below on a new mechanism to produce appreciable luminescence of the solid surface.

Our experiments<sup>(10)</sup> were confined to the demonstration that ion bombardment is deleterious to luminescence efficiency, where near-UV excitation was considered as the energy source. Nash<sup>(54)</sup> demonstrated the same effect much more completely for the case where ion bombardment also served as the source of excitation. In fact, luminescence was reduced by about half an order of magnitude following a dose of only  $10^{16} \text{ } ^+ \text{H}$  ions of 5 keV energy on most substances studied by him (1.6 yr on moon). Assuming penetration of  $0.4 \text{ } \mu$  into the sample, the energy deposited by this dose was about 25 eV/atom. Therefore luminescence is fairly efficiently destroyed by ion bombardment. On the other hand, we showed<sup>(10)</sup> that we could transfer the luminophor uranium glass from one surface to another by hydrogen ion sputtering without complete loss of luminescence. In view of the general pessimism about the involvement of the solar wind in lunar luminescence, we decided against further luminescence experiments at that time.

Recently we observed a luminescence phenomenon of apparently high efficiency which prompts further study. While the observation was very preliminary, we offer the following description. In a toroidal ring rf discharge in various low pressure gases we have observed strong emission of red light from the tube walls. The toroidal tube inside minor

diameter was 1.8 cm and the circumference was 80 cm. About 50 W of 40 Mc/s power was coupled into the gas by fitting a copper loop (80 cm long) closely around the inside of the toroid. In this arrangement an electric field like that in a betatron is developed along the length of the toroid. At a pressure of a few mTorr of Ar, for example, a bright plasma is formed and luminescence from the walls is negligible. But at the lowest pressures at which the discharge can be sustained ( $\approx 1$  mTorr Ar) the plasma becomes less bright and red light of brightness comparable to the plasma light is emitted from the walls. The walls are cool. The emission is in a 260 Å-wide band centered on 6230 Å for walls of either silica or Pyrex glass and for either Ar or He gas. That the emission is due to fast electrons may be concluded from the nondependence of gas and from the additional observation that an ion sheath at the wall cuts off the emission. An ion sheath at the wall can be induced simply by bringing the hand close to the tube wall owing to capacitive coupling which changes the boundary conditions. It is a general feature of sustained discharges of this type that the electron temperature increases markedly as the pressure is decreased from about  $2 p_{\min}$  to  $p_{\min}$ , where  $p_{\min}$  is the minimum pressure at which the discharge can be sustained in a tube of given cross section. We may estimate that the electrons responsible for the emission have an energy of the order of 10 eV. We can presently estimate the efficiency only crudely from the visual brightness relative to other light sources. We estimate 5 W in the red emission and 5 W in other plasma emissions in the visible region for 50 W rf power. Perhaps this estimate of 10%



conversion of rf (electron) power to light may be over-optimistic but we feel that the efficiency is greater than 1%.

A feature of special interest in the above observation is that the emission was not markedly sensitive to composition of the tube walls, i.e., the addition of considerable BaO and alkali oxides to SiO<sub>2</sub> to form Pyrex glass did not change either the wavelength or the luminescence efficiency markedly. We are concerned about whether the presence of rf fields is essential to the observed luminescence but have not had time to test this aspect. If the phenomenon is indeed electroluminescence, the following remarks are probably irrelevant.

A second feature of special interest is the low electron energy driving the emission (presumably by impact generation of carriers). This affords the possibility of accounting for certain of the alleged lunar luminescence events in terms of an aurora-like mechanism. Several events given special credence by Ney et al.<sup>(51)</sup> require emission of about  $10^2$  erg/cm<sup>2</sup> sec in an emission band 100 Å wide, or correspondingly more energy if the emission band is wider than 100 Å. They also discuss measurements of fluxes of electrons measured over the auroral zone in which electrons of greater than a minimum energy exhibited temporary energy fluxes of 10 to  $10^3$  erg/cm<sup>2</sup> sec. The minimum energy was from 1 to 50 keV in these measurements. These energy fluxes were lower limits because of the omission of electrons of lower energy. Therefore the possibility arises that a very efficient luminescent emission is driven by aurora-like electrons impacting on the solid moon. What remains to be shown is that aurora-like mechanisms exist for the interaction of the solar wind-moon system.

Auroras are generally associated with acceleration mechanisms driven by instabilities involving the solar wind and the large geomagnetic tail. But observation of a disturbed condition of the interplanetary medium outside the geomagnetic cavity was suggested<sup>(60)</sup> to be caused by a magnetohydrodynamic wake of the moon, which would be analogous to the geomagnetic tail. The suggestion has been disputed,<sup>(61,62)</sup> principally because it is not clear that an object as small as the moon should regularly have a wake.

A point to note is that if a lunar wake does exist at times, or even regularly, the energy flux of the solar wind over a large area can occasionally be transformed into energetic electron fluxes which can propagate along magnetic field lines tied to the (conducting) moon. Thereby the energy flux can actually exceed the average energy flux in the solar wind by an areal concentration of the energy flux, though the increase will probably not exceed an order of magnitude. Therefore temporary energy fluxes in excess of  $10^3 \text{ erg/cm}^2 \text{ sec}$  carried by electrons may occasionally impact on the moon where the whole surface may conceivably be capable of efficiently emitting light in several narrow bands at a rate of the order of  $10^2 \text{ erg/cm}^2 \text{ sec}$ . We emphasize again the necessity to establish that luminescent efficiencies are adequately large for essentially every silicate grain that rests on the lunar surface in certain extended lunar areas.

#### D. Formation of H<sub>2</sub>O Due to Hydrogen Ion Bombardment of Oxides

Blauth and Meyer<sup>(63)</sup> showed that atomic hydrogen can attack at least a portion of a monolayer of oxygen on glass and form water molecules. Since sputtering can reveal fresh surfaces for further attack, we were stimulated to investigate whether hydrogen sputtering of oxides is accompanied by water molecule formation. Our philosophy then was to sputter until several monolayers have certainly been removed and then measure the rate of H<sub>2</sub>O formation in the system which may be ascribed to hydrogen ion bombardment of an oxide sample. Since we chose to work first with ion bombardment in a hydrogen plasma, it was obvious that an appreciable background of H<sub>2</sub>O formation was to be expected from low-energy ion bombardment and H atom bombardment of the glass tube walls. Nevertheless, we expected this background source of H<sub>2</sub>O to become small after some period of conditioning of the walls. A second aspect of our philosophy was that it would not be necessary to detect the H<sub>2</sub>O molecules directly being emitted from the sample under bombardment. We planned to sample all the H<sub>2</sub>O formed as a consequence of the sample bombardment, whether formed directly on the sample or on a surface where material sputtered from the sample was collected. This economy is reasonable as a first approximation to demonstrate the order of magnitude of the efficiency for H<sub>2</sub>O formation.

Our first attempt<sup>(13)</sup> involved a cold trap at liquid N<sub>2</sub> temperature close to the bombarded sample. The plan was to collect H<sub>2</sub>O on the cold trap and pump away gases like H<sub>2</sub>, N<sub>2</sub>, O<sub>2</sub>, CO, CH<sub>4</sub>, and CO<sub>2</sub> which we did not expect to be trapped. To our surprise, large masses of H<sub>2</sub> were

trapped whenever a hydrogen plasma was maintained in the volume containing the cold trap. In fact, the amount of  $H_2$  trapped constituted many monolayers on the trap surface and prevented lengthy accumulations of  $H_2O$  because the desorbed  $H_2$  raised the total pressure in a 2.5 l. volume above the linear operating range of a gas analyzer in the volume. The desorption of  $H_2$  was irreversible so transfer of an active trapping substance to the cold trap surface by a hydrogen plasma was indicated. We showed that the probable active substance was carbon or an hydrogencous compound of high carbon content. The probable ultimate source of this substance was diffusion pump oil, despite careful bakeout and trapping.

We could show for  $CuO$  that about 1  $H_2O$  is formed per  $H_2^+$  incident, where the mean ion energy was roughly 500 eV. After sputtering  $CuO$  powder (largely chemical sputtering) until the sample surface was substantially metallic, the  $H_2O$  yield was an order of magnitude smaller. But on basalt powder the difficulty with  $H_2$  sorption prevented the reliable measurement of an  $H_2O$  yield, though it was possible to conclude that the yield was small. This was to be expected since physical sputtering yields in this case are also small,  $\sim 10^{-2}$  atom/ion, and the  $H_2O$  yield should not exceed the rate of liberation of O-atoms from the sample at equilibrium.

We therefore modified the system to permit flow analysis by installing the gas analyzer between the diffusion pump and a special valve. The valve consisted of an iron disk of 2.7 cm diameter with a central aperture of 0.1 cm. The valve could be actuated magnetically through the

tube walls. The valve decreased the pumping speed when closed by a factor of 16 and permitted the gas analyzer to operate in  $1 \times 10^{-3}$  Torr of  $H_2$ . At this pressure the resolution of the gas analyzer was not appreciably affected by gas scattering while adequate pressure for an rf discharge was obtained in the main volume.

Experiments with the flow system are as yet inconclusive due to delays involving breakdown of the gas analyzer equipment except for one observation. Even after lengthy bakeout and sputtering of a basalt powder sample, we observed that ion bombardment following a short bakeout of the system is accompanied by a gradually rising  $H_2O$  output. This may be the consequence of a rising concentration in the sample of some precursor to  $H_2O$  or it may simply be due to gradual heating of the sample followed by  $H_2O$  desorption which is not a genuine product of the hydrogen ion bombardment. According to Stecher and Williams,<sup>(64)</sup> molecule formation on small solid grains under low pressure conditions takes place principally by chemical-exchange reactions. Therefore  $H_2O$  release should be expected to follow a gradual buildup of OH concentration at or near the solid silicate surface when bombarded with hydrogen ions. In this case the  $H_2O$  release is consistent with  $H_2O$  formation at roughly the sputtering rate. If the  $H_2O$  release was merely  $H_2O$  desorbed from the sample, the  $H_2O$  formation was much weaker. Efforts are continuing towards a better understanding of these effects.

## VI. ACKNOWLEDGEMENTS

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## VII. LIST OF REFERENCES

1. General Mills Electronics Division. Investigation of sputtering effects on the moon's surface, by G. K. Wehner, D. L. Rosenberg, and C. E. KenKnight. Contract NAWw-751. Report No. 2414. First Quarterly Status Report (25 April-24 July 1963).
2. Ibid. Report No. 2476. Second Quarterly Status Report (25 July-24 Oct. 1963).
3. Ibid. Report No. 2527. Third Quarterly Status Report (25 Oct. 1963-24 Jan. 1964).
4. Ibid. Report No. 2565. Fourth Quarterly Status Report (25 Jan.-24 April 1964).
5. Applied Science Division, Litton Systems, Inc. Investigation of sputtering effects on the moon's surface, by G. K. Wehner, D. L. Rosenberg, and C. E. KenKnight. Contract NASw-751. Report No. 2613. Fifth Quarterly Status Report (25 April-24 July 1964).
6. Ibid. Report No. 2669. Sixth Quarterly Status Report (25 July-24 Oct. 1964).
7. Ibid. Report No. 2722. Seventh Quarterly Status Report (25 Oct. 1964-24 Jan. 1965).
8. Ibid. Report No. 2792. Eighth Quarterly Status Report (25 Jan.-24 April 1965).
9. Ibid. Report No. 2845. Ninth Quarterly Status Report (25 April-24 July 1965).
10. Ibid. Report No. 2910. Tenth Quarterly Status Report (25 July-24 Oct. 1965).
11. Ibid. Report No. 2957. Eleventh Quarterly Status Report (25 Oct. 1965-24 Feb. 1966).
12. Ibid. Report No. 2986. Twelfth Quarterly Status Report (25 Feb.-24 April 1966).
13. Ibid. Report No. 3037. Thirteenth Quarterly Status Report (25 April-2 Sept. 1966).
14. Ibid. Investigation of sputtering effects on the moon's surface, by G. K. Wehner and C. E. KenKnight. Report No. 3070. Fourteenth Quarterly Status Report (2 Sept.-2 Dec. 1966).

15. Ibid. Report No. 3098. Fifteenth Quarterly Status Report (2 Dec. 1966-2 March 1967).
16. G. K. Wehner, C. E. KenKnight, and D. L. Rosenberg. Sputtering rates under solar-wind bombardment. Planet. Space Sci. 11: 885-895 (1963).
17. D. L. Rosenberg and G. K. Wehner. Darkening of powdered basalt by simulated solar-wind bombardment. J. Geophys. Res. 69(15): 3307-3308 (1964).
18. T. Gehrels, T. Coffeen, and D. Owings. Wavelength dependence of polarization. 3. The lunar surface. Astron. J. 69(10): 826-852 (1964).
19. G. Rougier. Total photoelectric photometry of the moon. Ann. Observ. Strasbourg 2(3): 205-239 (1933).
20. B. Hapke. A theoretical photometric function for the lunar surface. J. Geophys. Res. 68(15): 4571-4586 (1963).
21. D. B. Nash. Proton-irradiation darkening of rock powders and solar-wind darkening of the moon. J. Geophys. Res. 72 (to be published 15 June 1967).
22. R. T. Greer and B. W. Hapke. Electron microprobe characterization of microcrystalline powders darkened by simulated solar-wind irradiation. J. Geophys. Res. 72 (to be published 15 June 1967).
23. M. Neugebauer and C. W. Snyder. Mariner 2 observations of the solar wind. 1. Average properties. J. Geophys. Res. 71(19): 4469-4484 (1966).
24. V. R. Eshleman et al. The interplanetary electron number density from preliminary analysis of the Pioneer 6 radio propagation experiment. J. Geophys. Res. 71(13): 3325-3327 (1966).
25. J. H. Wolfe, R. W. Silva, D. D. McKibbin, and R. H. Mason. The compositional, anisotropic, and nonradial flow characteristics of the solar wind. J. Geophys. Res. 71(13): 3329-3335 (1966).
26. A. J. Lazarus, H. S. Bridge, and J. Davis. Preliminary results from the Pioneer 6 M.I.T. plasma experiment. J. Geophys. Res. 71(15): 3787-3790 (1966).
27. J. H. Wolfe, R. W. Silva, and M. A. Myers. Observations of the solar wind during the flight of Imp 1 (Explorer 18). J. Geophys. Res. 71(5): 1319-1340 (1966).



28. S. Biswas, C. E. Fichtel, and D. E. Guss. Solar cosmic-ray multiply-charged nuclei and the July 18, 1961, solar event. *J. Geophys. Res.* 71(17): 4071-4077 (1966) and earlier references therein.
29. J. Lemaire. Evaporation and hydrodynamical atmospheric models. *Ann. Astrophys.* 29(3): 197-203 (1966).
30. J. T. Jefferies and F. Q. Orrall. Loop prominences and coronal condensations. 3. The abundances of iron and calcium. *Astrophys. J.* 145(1): 231-236 (1966).
31. J. Brandt. The heavy element abundances in the solar wind. Abstract. *Astron. J.* 70(9): 668-669 (1965).
32. Applied Science Division, Litton Systems, Inc. Surface bombardment studies, by G. K. Wehner, G. S. Anderson, and C. E. KenKnight. Contract AT(11-1)-722. Report No. 3031. Final Report (16 Feb. 1959-14 Aug. 1966).
33. P. K. Rol. Sputtering of copper due to bombardment by ions from 5 to 25 keV. Thesis. Amsterdam (1960).
34. P. K. Rol, J. M. Fluit, and J. Kistemaker. Sputtering of copper by bombardment with ions of 5-25 keV. *Physica* 26: 1000-1008 (1960).
35. Ibid. Theoretical aspects of cathode sputtering in the energy range of 5-25 keV. *Physica* 26: 1009-1011 (1960).
36. P. K. Rol, J. M. Fluit, and J. Kistemaker. Sputtering of copper by ion bombardment in the energy range of 5-25 keV. Progress in Astronautics and Rocketry. Vol. 5. Electrostatic Propulsion (Academic Press, Inc., N.Y., 1961) pp. 203-216.
37. D. T. Goldman and A. Simon. Theory of sputtering by high-speed ions. *Phys. Rev.* 111: 383-386 (1958).
38. D. L. Harris. Photometry and colorimetry of planets and satellites. The Solar System. 3. Planets and Satellites, edited by G. P. Kuiper and B. M. Middlehurst (Univ. of Chicago Press, Chicago, 1961) pp. 272-342.
39. B. Hapke and H. Van Horn. Photometric studies of complex surfaces with applications to the moon. *J. Geophys. Res.* 68(15): 4545-4570 (1963).

40. B. Hapke. Optical properties of the moon's surface. The Nature of the Lunar Surface, edited by W. Ness, D. Menzel, and J. O'Keefe (Johns Hopkins Press, Baltimore, 1966) pp. 141-154.
41. F. L. Whipple. On the lunar dust layer. Vistas in Astronautics. 2, edited by M. Alperin and H. F. Gregory (Pergamon Press, New York, 1959) pp. 267-272.
42. W. M. Alexander and J. L. Bohn. Surveyor lunar ejecta experiment. J. Geophys. Res. 72(2): 845-850 (1967).
43. T. W. Rackham. Photographic colorimetry of the moon in narrow passbands. Icarus 3: 45-51 (1964).
44. G. K. Wehner. Sputtering effects on the moon's surface. Am. Rocket Soc. J. 31(3): 438-439 (1961).
45. R. Smoluchowski. Structure and coherency of the lunar dust layer. J. Geophys. Res. 71(6): 1569-1574 (1966).
46. R. V. Stuart and G. K. Wehner. Energy distribution of sputtered Cu atoms. J. Appl. Phys. 35: 1819-1824 (1964) and references reviewed therein.
47. H. Oechsner and H. Reichert. Energies of neutral sputtered particles. Phys. Letters 23: 90-92 (1966).
48. L. D. Jaffe. Depth of the lunar dust. J. Geophys. Res. 70(24): 6129-6138 (1965).
49. L. D. Jaffe. Lunar dust depth in Mare Cognitum. J. Geophys. Res. 71(4): 1095-1103 (1966).
50. J. A. Bastin. Small scale lunar roughness. Nature 212: 171-173 (1966).
51. E. P. Ney, N. J. Woolf, and R. J. Collins. Mechanisms for lunar luminescence. J. Geophys. Res. 71(7): 1787-1793 (1966).
52. J. M. Burley and B. M. Middlehurst. Apparent lunar activity: historial review. Proc. Natl. Acad. Sci. U.S. 55: 1007-1011 (1966).
53. K. H. Sun and J. L. Gonzalez. Thermoluminescence of the moon. Nature 212: 23-25 (1966).
54. D. B. Nash. Proton-excited luminescence of silicates: experimental results and lunar implications. J. Geophys. Res. 71(10): 2517-2534 (1966).

55. J. Schutten and Th. van Dijk. Luminescence caused by proton impact with special reference to the lunar surface. Nature 211: 470-471 (1966).
56. B. M. Middlehurst. Lunar transient phenomena. Icarus 6: 140-142 (1967).
57. N. A. Kozyrev. Physical observations of the lunar surface. Physics and Astronomy of the Moon, edited by Z. Kopal (Academic Press, N.Y., 1962) pp. 361-383.
58. Z. Kopal. Luminescence of the moon and solar activity. The Nature of the Lunar Surface, edited by W. N. Ness, D. H. Menzel, and J. A. O'Keefe (Johns Hopkins Press, Baltimore, 1966) pp. 173-183. The right-hand photographs in his Fig. 9-5 are interchanged.
59. Z. Kopal and T. W. Rackham. Excitation of lunar luminescence by solar activity. Icarus 2: 481-500 (1963).
60. N. F. Ness. The magnetohydrodynamic wake of the moon. J. Geophys. Res. 70(3): 517-534 (1965).
61. J. Hirshberg. Discussion of paper by N. F. Ness, The magnetohydrodynamic wake of the moon. Ibid. 71(17): 4202-4204 (1966).
62. N. F. Ness. Reply. Ibid. 71(17): 4205-4206 (1966).
63. E. W. Blauth and E. H. Meyer. Zur Gasaufzuehrung in einer HF-Gasentladung. Z. Angew. Phys. 19: 549-552 (1965).
64. T. P. Stecher and D. A. Williams. Interstellar molecule formation. Astrophys. J. 146(1): 88-103 (1966).